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Retention of lake-derived nitrogen (N) was studied in four geomorphically distinct lake outlets located in arctic Alaska. ^{15}N ammonium chloride tracer was experimentally added to Lakes NE-12, GTH 99, GTH 153 and GTH 114 at the beginning of the arctic summer each year from 2005 to 2008 and monitored in *Carex*, the dominant riparian plant, fine benthic organic matter (FBOM) and seston along the outlet streams. In this study, samples from each compartment were taken pre-enrichment and post-enrichment 2008, then processed and analyzed for $\delta^{15}N$. Pre-enrichment samples measured N retained from ^{15}N enrichment in summers of 2005-2007, and differences between pre-enrichment and post-enrichment samples measured mobility of N over the summer season. A similar decrease in $\delta^{15}N$ values of pre- and post-enrichment *Carex* samples in all lake outlets suggested that N supporting biomass in the 2008 season was derived from previous enrichment seasons. Differences in pre- and post-enrichment $\delta^{15}N$ values for FBOM and seston in three of the four outlets suggest mobile particulate matter was only retained during the summer. Tight coupling of FBOM and seston was observed in GTH 99 outlet where both compartments showed similar patterns of enrichment. Lateral retention of ^{15}N was detected up to 2 m from the main channel of GTH 114 outlet. Higher gradient streams had a pronounced difference in longitudinal patterns of FBOM and seston, which was not found in lower gradient streams. However, higher amounts of previously supplied ^{15}N were found in lower gradient streams. Influence of discharge on

uptake length (S_W) was analyzed for each sampling time period in compartments with at least three significant S_W. Discharge did not have a significant effect on S_W of pre-enrichment *Carex*, or post-enrichment FBOM and seston. Exponential regression slopes of uptake from each lake outlet were compared. Results indicated a significant difference between Lake GTH 153 outlet, a beaded stream, and Lake GTH 114 outlet, a meandering wetland stream. These data suggest that differences in stream geomorphology affect temporal dynamics and compartments for N retention. Results from this study give evidence to the importance of arctic lake outlets as N sinks and that geomorphic setting determines the efficiency of N retention.

RETENTION OF LAKE-DERIVED NITROGEN IN ARCTIC STREAMS WITH DIFFERENT GEOMORPHIC SETTINGS EVALUATED USING A ^{15}N STABLE ISOTOPE TRACER

by

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CHAPTER I

INTRODUCTION

Nitrogen is a dynamic element in aquatic ecosystems whose availability can limit productivity or initiate eutrophication. A more complete understanding of nitrogen cycling and retention is needed to predict the effects of increased inputs of fixed nitrogen in ecosystems (Mulholland *et al* 2000). Issues that are incompletely understood include knowledge of how landscape heterogeneity affects immobilization of inorganic N and which ecosystem processes and compartments are most important in the long-term retention of nitrogen.

In freshwater systems, three processes contribute to nitrogen retention and loss: denitrification, incorporation in sediment as particulate matter, and uptake by aquatic organisms (Saunders and Kalff 2001). Denitrification permanently removes fixed N from aquatic systems by releasing it into the air as N_2. Nitrogen becomes incorporated in sediment by accumulating as particulate matter. In addition, macrophytes are able to store nitrogen in their shoots and roots during a growing season, thereby serving as nitrogen sinks in an aquatic system. Macrophytes also influence an aquatic system by decreasing organic material and nutrient fluxes to downstream systems during a growing season (Stream Bryophyte Group 1999).

The term nutrient spiraling describes the simultaneous processes of nutrient cycling and downstream transport (Newbold *et al* 1981). The study of solute dynamics

in streams describes rates of transport and transformation of solutes which is useful in understanding their availability and significance in an aquatic ecosystem (Mulholland *et al* 2001, Webster & Ehrman 1996). Solute dynamics are also used to quantify various hydrodynamic properties in streams. Nutrients alternate between periods of movement and periods of immobility when trapped in different benthic components. Nutrient uptake length is an important parameter in determining nutrient cycling in streams. Uptake length (S_W) is defined as the mean distance traveled by a nutrient atom dissolved in water before uptake by biota or sorption onto particulate matter (Newbold *et al* 1981, Stream Solute Workshop 1990). Uptake velocity (v_f) is another parameter that measures uptake efficiency relative to nutrient availability (Davis & Minshall 1999) and standardizes uptake length for discharge (depth and velocity) (Stream Solute Workshop 1990). Finally, areal uptake (U) measures the amount of nutrient removed per unit area per unit time.

Most variation in uptake length is attributed to differences in physical characteristics including current velocity and stream depth, which are correlated with discharge (Peterson *et al* 2001). Water movement can have a strong influence on the biogeochemistry of a system (Brookshire *et al* 2005). N uptake and retention should be greatest where hydrologic residence time is longest (Cirmo & McDonnell 1997). This implies that slow-moving water storage areas such as riparian wetlands have the potential to hold a greater amount of N than a faster-moving channel flow area. High densities of macrophyte beds in these areas can also influence water current and sediment conditions (Stream Bryophyte Group 1999, White & Hendricks 2000).

Geomorphic conditions within aquatic ecosystems can affect nutrient cycling. By determining which aquatic ecosystem types and components retain nitrogen most efficiently, e.g. channels, wetlands, pools, etc., management strategies can be designed to utilize natural retention capacities (Jansson 1994). Wetlands have been used to help protect adjacent aquatic systems against anthropogenic sources of nitrogen-rich wastewater (Saunders and Kalff 2001). Also, water velocity is reduced in wetlands, allowing fine particulate matter to settle to the bottom where macrophyte roots help stabilize benthic sediment (Sand-Jensen & Mabus 1996).

Important information on nitrogen dynamics has come from input-output budgets and/or from experimental additions of ammonium or nitrate (Mulholland 2000). However, these methods have limited ability to explicitly determine uptake, retention, and fate of nitrogen. Rates of uptake, transformation, and retention could not be determined because either the simultaneous processes of uptake, release, and downstream transport could not be measured independently, or these rates were changed by nutrient enrichment. To avoid these shortcomings, stable isotope analysis of naturally occurring and tracer enriched ^{15}N has been used successfully to determine natural movements of nitrogen in ecosystems (Peterson & Fry 1987). Ratios of $^{15}N/\ ^{14}N$ are reported in parts per thousand (‰) different from atmospheric ^{15}N, which has a constant isotopic composition, where: $\delta\ ^{15}N = [(R_{sample}/ R_{standard}) \times 1000$ with $R = {}^{15}N:{}^{14}N$. Distinct $^{15}N:{}^{14}N$ ratios can help identify different pools of nitrogen. Anthropogenic sources such as waste and fertilizer all reflect specific $\delta^{15}N$ signatures permitting inference regarding N sources of and processes within ecosystems.

Lake outlets provide a transition between lentic and lotic habitats (Wotten 1995). Biotic communities of these ecosystems are characteristic of streams and rivers. The chemistry of water flowing over these communities depends on outlet geomorphology and temperature, reflecting a transition between lentic and lotic ecosystems. Arctic regions provide desirable locations to study movement and retention of nutrients in lake outlets. These Arctic aquatic ecosystems are biologically simple, exposed to continuous light during the growing season with low to no shading by riparian vegetation and are free of anthropogenic impacts (Hullar 1989). Although primary production is limited mainly by nitrogen in Arctic tundra ecosystems (Shaver and Chapin 1991), arctic tundra is functionally and structurally diverse across landscapes (Giblin 1996). Natural abundances of ^{15}N in soil and plants near Toolik Lake Field Station, where tundra N dynamics have been well studied, are very low. Soil values have increasing $\delta^{15}N$ values with depth of horizon in wet sedge tundra, where $\delta^{15}N$ values increased from –2.5‰ in surface peat to 2.9‰ 30cm below the surface (Nadelhoffer *et al* 1996). Sedges in wet meadows have lower $\delta\ ^{15}N$ values at –3.8‰.

^{15}N is useful for the investigation of N uptake, retention, and transport along lake outlets. The isotope is assimilated by plants and moves into the shoots through the xylem (Oghoghorie & Pate 1971). ^{15}N applied to sediments is immobilized as NH_4, and therefore, retained in an aquatic system (Rivera-Monroy & Twilley 1996). Finally, ^{15}N measured in the particulate organic matter suspended in the water column allows for determination of the amount of N in transport down the lake outlet (Legendre & Gosselin 1996).

This study focused on the fate of nitrogen within outlets of oligotrophic lakes located in arctic Alaska. Enrichment of ^{15}N using ^{15}N ammonium chloride was applied to upstream lakes allowing for the measurements of transport and retention of ^{15}N downstream in lake outlets with different geomorphologies. Lateral movement of ^{15}N from the main channel of a wetland outlet was also measured. Nitrogen uptake was observed in macrophytes, N retention in sediment, and N transport in seston. It was hypothesized that N retention in all three compartments would decrease as distance from the lake nutrient source increased and there would be more N retention in habitats with greater water residence time.

CHAPTER II

METHODS

Site Description

The study was conducted in four lake outlets located on the North Slope of the Brooks Range near Toolik Lake Field Station (68º38'N, 149º38'W) in arctic Alaska (Fig. 1, Table 1). Upstream lakes of all study outlets were oligotrophic with dissolved inorganic nitrogen concentrations ranging from <.05 µM to 17 µM (Whalen *et al* 2008, Whalen *et al* 2006, Chalfant 2004). Lake GTH 114 outlet was a wetland drained by a meandering channel with peat sediment which flowed 208 m west into Lake GTH 113. The sedge *Carex aquatilis* was the dominant vegetation. Lake GTH 99 outlet flowed 95 m south into Lake GTH 100. The channel was also surrounded by *Carex,* but was confined, varied little in contour, and contained peat substrate. Lake GTH 153 outlet showed the most variation in landscape of the four lakes and was the only transect without a connecting lake. The 512 m study reach contained areas of confined channels (runs and riffles), wetland, and beads; all with peat sediment. The riparian zone was dominated by *Carex* and willow (*Salix*). Lake NE-12 outlet was primarily a confined channel with a mixture of gravel and peat sediment and flowed west into Lake GTH 156.

Lakes NE-12, GTH 153, GTH 99 and GTH 114 were enriched with a ^{15}N ammonium chloride (NH_4Cl) tracer four consecutive summers (2005, 2006, 2007 and

2008). The tracer was added to the epilimnia of the four lakes in late June and entered the outlet throughout the open water season.

Experimental Design

Three N compartments were sampled in order to better understand the fate of N in arctic streams. *Carex* was sampled to access the fate of dissolved ^{15}N retained in sediments and then taken up by riparian plants. Fine benthic organic matter (FBOM) includes detritus and algal particles. FBOM samples were used to determine particulate ^{15}N retention. Seston was sampled to evaluate particulate N in transport along the outlets.

A cross-sectional stream profile was made at the first and last sample stations of each outlet stream in order to calculate discharge. Flow velocity was determined in all outlets using a flowmeter. Discharges are presented as averages of two sites within transects. Stream gradient was calculated with ArcGIS software used to determine elevation from the Digital Elevation Model of the Toolik Lake region.

Lake NE-12 outlet had 13 stations along the main channel at 10 m intervals. The outlet of Lake GTH 153 was sampled at 14 stations along the main channel at 40 m intervals and GTH 99 had 10 stations at 10 m intervals. Lake GTH 114 outlet was sampled at 14 different sampling stations at 15 m intervals along the main channel of the outlet wetland. In order to avoid disturbing downstream sites, sample collection began at the downstream end of the outlet and continued upstream toward the ^{15}N enriched lake.

Lateral retention of N was studied in Lake GTH 114 outlet. Each channel site also had sample transect sites located later to the main channel for 2 m on each side (north and south of the main flow) with sample sites set every 1 m. The lateral grid

included a total of 56 sites. Samples from the Lake GTH 114 lateral grid were selected for analysis based on surrounding geomorphology. The valley is steeper on the north side of the channel, so more lateral dispersion of ^{15}N from the channel southward might be expected due to groundwater flow. Only samples from the south side were analyzed due to funding constraints.

Sample Collection

Samples of *Carex*, FBOM, and seston from all transects were collected prior to ^{15}N addition in late June 2008 for determination of ^{15}N retention from enrichment in previous summers. Samples were collected again at the end of the summer season for determination of retention of ^{15}N from the summer of 2008 enrichment.

For each of the stations within the main channels of Lakes NE-12, GTH 153, GTH 99 and GTH 114 outlets and the lateral transect of Lake GTH 114 outlet, samples of *Carex* were clipped from the tops of the blades. Samples were thoroughly dried in a drying oven before being processing for isotopic analysis.

Samples of FBOM from Lake NE-12, GTH 153, GTH 99 and GTH 114 outlets (main channel and lateral grid) were collected using a suction bulb. The bulb was lightly dragged along the sediment surface of the outlet to collect particulate matter. Contents obtained were placed into labeled 150ml poly bottles. Excess water was decanted and the samples were allowed to dry.

Seston was collected from sample stations to determine amounts of suspended ^{15}N within the water column of the outlets. One cubitainer (4 liters) of water was filled for each sample station in NE-12, GTH 153 and GTH 99 outlets. Seston was not collected

from GTH 114 outlet because it was too shallow to prevent simultaneous collection of FBOM. Sample water from each outlet was filtered through triplicate 47 mm glass microfiber filters using vacuum filtration. Necessary volumes of water were filtered to effectively clog each filter, which differed for each sample station. Before use, filters were ashed to burn off residual organic material. Filters were thoroughly dried in a drying oven before processing for isotopic analysis.

Stable Isotope Analysis

All *Carex*, FBOM and seston samples were prepared for ^{15}N isotopic analysis by drying at 60°C for no less than 48 hours. In preparation for isotope processing, appropriate amounts of samples were weighed and placed in trays for analysis by the University of California Davis Isotope Lab. *Carex* blades (3-4 mg) were crushed and placed into 5x9 mm tin capsules. FBOM samples (3-4 mg) were crushed and placed into 4x6 mm capsules. For seston samples, one quarter of each filter was cut and placed into 5x9 mm tin capsules. Samples were analyzed using isotope ratio mass spectrometry.

Calculating Solute Dynamics

Uptake length was calculated to measure effectiveness of nutrient retention in *Carex* and FBOM of Lake NE-12, GTH 153, GTH 99 and GTH 114 outlets and calculated for seston from Lake NE-12, GTH 153 and GTH 99:

$$S_W = 1/k$$

The natural log of background corrected $\delta\ ^{15}N$ values were plotted verses distance downstream for each outlet channel. The slope (k) of each exponential regression is the distance specific uptake rate. A multiple regression was used to determine significance

of the stream as a predictor and to compare regression slopes from each lake outlet. The inverse of the distance specific uptake rate is the uptake length (S_W). This parameter measures the length of movement a nutrient molecule travels downstream before being immobilized into *Carex* and FBOM. Uptake lengths were calculated without the use of NH_4 concentrations, but note that S_w is independent of NH_4 concentrations.

Statistical Analysis

Background values $\delta^{15}N$ were determined by sampling *Carex,* FBOM and seston from non-enriched streams near Toolik Lake Field Station that were similar in landscape setting to each respective experimental outlet. These values were subtracted from $\delta^{15}N$ values for corresponding sample types collected from the GTH 114, GTH 99, GTH 153 and NE-12 outlets for background correction.

A one-way between-groups analysis of covariance (ANCOVA) was used to determine similarity in patterns of pre-enrichment and post-enrichment *Carex,* FBOM and seston samples. Distances (m) downstream of the nutrient source were used as the covariate in analyses. Preliminary tests were used to determine whether data adhered to assumptions of normality, linearity, homogeneity of variances and homogeneity of regression slopes. All data tested normal using the Kolmogrov-Smirnov test. Sets of *Carex*, FBOM and seston that violated assumptions of linearity, variance homogeneity and/ or had a significant interaction were corrected with a log transformation.

A multiple regression model was used to compare regression coefficients between models. The model defined below was used to determine significance of outlet location on distance specific uptake rates.

$\Sigma[Y] = \beta_0 + \beta_1 \text{distance-} + \beta_2 I_A + \beta_3 I_B + \beta_4 I_C + \beta_5 (\text{dis}*I_A) + \beta_6(\text{dis}*I_B) + \beta_7(\text{dis}*I_C)$ where β values represent regression coefficients, I_A, I_B and I_C represent dummy variables for lakes (a fourth dummy variable was not necessary and is represented by the constant) and dis represents distance downstream. A covariance matrix supplied by the regression output was used to calculate t statistics. These t statistics were used to determine the effect of each outlet location on the overall model and to compare slopes between lake outlets.

Influence of uptake length by discharge was determined for both pre- and post-enrichment samples using a one-way between-groups analysis (ANOVA). Only compartments with at least three significant uptake lengths for each time period were used in the regressions.

CHAPTER III

RESULTS

Lake NE-12 Outlet

Carex showed an overall decrease in $\delta^{15}N$ values with distance downstream of the Lake NE-12 nutrient source in both pre- and post-enrichment samples (Fig. 2A, $p = .001$). However, $\delta^{15}N$ values from pre- and post-enrichment did not differ significantly ($p = .767$). The regression slope (-0.008) was significant for pre-enrichment *Carex* with an estimated uptake length of 125 m (Table 2). The regression slope for post-enrichment *Carex*, however, was not significant, therefore uptake length was not calculated.

FBOM showed a significant decrease in $\delta^{15}N$ moving downstream from the nutrient source (Fig. 2B, $p < .001$). However, pre-enrichment values showed little overall change in $\delta^{15}N$ with distance downstream with a regression slope of -0.005 and uptake length of 200 m (Table 3). Post-enrichment $\delta^{15}N$ values decreased from 88.52‰ at 10 m to 41.39‰ at 50 m with little fluctuation further distance downstream. The regression slope in post-enrichment samples was -0.008 with an uptake length of 125 m. Post-enrichment samples had significantly higher $\delta^{15}N$ values than pre-enrichment samples ($p < .001$).

A significant decreasing trend downstream was found in seston (Fig. 2C, $p = .013$). However, pre-enrichment samples had little fluctuation downstream from the lake, similar to the pattern found in pre-enrichment FBOM, indicating that

^{15}N added in previous years was eventually distributed throughout the stream reach. However, seston post-enrichment samples had significantly higher $\delta^{15}N$ values than pre-enrichment ($p < .001$). The regression slope for pre-enrichment samples was not significant. The regression slope for post-enrichment samples, however, was -0.005 with an estimated uptake length of 200 m (Table 4). As with FBOM, the uptake length for seston was calculated to be longer than the stream itself, suggesting low retention of ^{15}N in these compartments.

Lake GTH 153 Outlet

Background corrected $\delta^{15}N$ enrichment values in *Carex* ranged from -.87‰ to 8.92‰ (Fig. 3A). There was a decline in both pre- and post-enrichment values between 208m and 368m. There was no significant difference in $\delta^{15}N$ between pre- and post-enrichment ($p = .183$), or with distance downstream ($p = .617$). The regression slopes for pre- and post-enrichment samples were not significant (Table 2).

FBOM from pre and post-enrichment in the GTH 153 outlet both showed a similar pattern of fluctuation downstream; with low and high values shown in many of the same sample stations (Fig. 3B). There was not a significant difference between pre and post-enrichment $\delta^{15}N$ ($p = .216$). There was however a significant decrease in $\delta^{15}N$ with distance downstream overall ($p < .001$). Pre-enrichment samples did not show a significant regression slope, while post-enrichment samples had a regression slope of -0.006 and uptake length of 166 m (Table 3).

$\delta^{15}N$ values in seston (Fig. 3C) showed no significant difference between pre and post-enrichment ($p = .654$) or between distances downstream ($p = .344$). The estimated

regression slope for pre-enrichment seston was positive at 0.003 with an uptake length of 333 m (Table 4), whereas the post-enrichment samples had a regression slope of -0.002 and an uptake length of 500 m.

Lake GTH 99 Outlet

$\delta^{15}N$ signatures in *Carex* were not significantly different between pre and post-enrichment (Fig. 4A, $p = .469$). Highest $\delta^{15}N$ values were found closest to the lake source with a steep decrease after this sample station in both pre- and post-enrichment. There was a significant effect of downstream distance ($p = .005$). *Carex* pre-enrichment regression slope was not significant, where the post-enrichment regression slope was 0.015 with an estimated uptake length of 125 m (Table 2).

Post-enrichment samples of FBOM in the GTH 99 outlet had higher values of $\delta^{15}N$ than pre-enrichment samples (Fig. 4B, $p < .001$). There was a significant decrease in FBOM $\delta^{15}N$ with distance downstream ($p = .028$). However, the regression slope calculated separately for pre-enrichment FBOM was non-significant.(Table 3). In contrast, the post-enrichment regression slope was significant at -0.010 with an uptake length of 100 m.

Post-enrichment seston samples had higher $\delta^{15}N$ values than pre-enrichment samples (Fig. 4C, $p < .001$). Post-enrichment had more fluctuation downstream while pre-enrichment ^{15}N was more evenly distributed throughout the stream. $\delta^{15}N$ also showed a significant pattern with distance downstream ($p = .003$). However, the pre-enrichment regression slope was not significant whereas the post-enrichment regression slope was -0.008 with an uptake length of 125 m (Table 4).

Lake GTH 114 Outlet

Channel $\delta^{15}N$ values in *Carex* did not differ between pre- and post- enrichment samples ($p = .432$). Distance from the lake nutrient source, however, was significant ($p < .001$). Pre-enrichment samples of *Carex* in Lake GTH 114 outlet had a regression slope of -0.010 and uptake length of 100 m (Table 2). Post-enrichment samples had a regression slope of -0.006 and uptake length of 167 m. *Carex* $\delta^{15}N$ values of samples taken from the lateral grid in Lake GTH 114 outlet showed a decrease in $\delta^{15}N$ moving downstream from the nutrient source. Pre- and post-enrichment from 1 m south show a similar fluctuation pattern of decrease downstream and contain similar amounts of ^{15}N. This is reflected in ANCOVA data showing there was no significant difference between pre and post-enrichment samples (Fig. 5, $p = .363$). However, change in $\delta^{15}N$ with distance downstream was significant ($p=.005$). Similarly, $\delta^{15}N$ values from 2 m south pre and post-enrichment samples had comparable patterns of decrease. There was not a significant difference between pre and post-enrichment values ($p=.737$). There was a significant decrease in N retention, however, with distance downstream ($p = .001$). There was no significant difference between channel samples versus lateral samples in pre-enrichment *Carex* $\delta^{15}N$ values ($p = 176$). Samples at 1 m were found to be significantly higher in post-enrichment samples ($p = .020$). However, the pattern of decrease downstream is very similar between channel and lateral grid samples, with high and low values found at similar locations within the stream.

Post-enrichment FBOM $\delta^{15}N$ values were significantly higher than pre-enrichment samples from the Lake GTH 114 outlet channel (Fig. 6, $p = .026$). Although

there was a significant difference found between early and late season samples, the difference in values was not as large as that seen in the higher gradient outlets, NE-12 and GTH 99 (Table 1). The channel regression slope for pre-enrichment samples was -0.009 with estimated uptake length of 111 m (Table 3). Post-enrichment samples had a regression slope of -0.007 and an uptake length of 143 m (Table 3). FBOM samples from 1 m and 2 m south in the grid also showed a decrease in $\delta^{15}N$ values moving downstream along the main channel. The difference between pre- and post- enrichment values south were not significant ($p = .094$). There was a significant difference between sample sites moving downstream ($p < .001$). *Carex* at 2 m south did not differ between pre- and post-enrichment ($p = .131$) but did have significant decrease in $\delta^{15}N$ values downstream ($p = .008$). There was no significant difference between channel samples versus lateral samples in either pre- ($p = .498$) or post-enrichment ($p = .468$) samples.

Multiple Regression

A multiple regression model was used to determine significance of outlet location on distance specific uptake rates, represented by regression coefficients. Calculations of t statistics using output supplied by covariance matrices indicated a significant difference between the slopes of the GTH 153 outlet and GTH 114 outlet in pre-enrichment FBOM. This significant difference between slopes was suggested by a large t statistic (Table 5, $t = 2$). All other slope variations between lakes in pre- and post-enrichment FBOM were not found to be significant.

Uptake Length versus Discharge

Only pre-enrichment *Carex* and post-enrichment FBOM and seston presented enough significant values for uptake lengths to relate to discharge. Outlet discharge was not found to be a significant predictor of uptake length for pre-enrichment *Carex* (Fig. 7A, $p = .356$, $R^2 = .719$) or post-enrichment FBOM (Fig. 7B, $p = .794$, $R^2 = .042$) and seston (Fig. 7B, $p = .999$, $R^2 < .001$), suggesting discharge may be less important in determining uptake lengths of the study outlets than factors such as stream gradient.

CHAPTER IV

DISCUSSION

This study explores N retention among different N compartments in arctic lake outlet streams in different geomorphic settings. N retention is studied by using uptake length measurements of a ^{15}N tracer as a surrogate of N retention over winter versus retention during the summer season. N-uptake studies have taken place in a larger arctic tundra river, the Kuparuk River (Peterson et al. 1997) and in low order non-outlet streams on the North Slope of Alaska (Wollheim et al. 2001). The present study contrasts with previous work because lakes provide the N source. Over winter N retention was measured in samples collected early the following summer, and the role of a riparian sedge (*Carex*) is evaluated as a retention compartment.

Comparison of ^{15}N retention among compartments

It was predicted that N would be differentially retained in *Carex*, FBOM and seston compartments. NH_4^+ uptake has been studied in many stream ecosystems using ^{15}N-NH_4Cl to measure NH_4^+ uptake directly and using epilithon $\delta^{15}N$ as a surrogate for NH_4^+ uptake (Peterson *et al* 1997, Hamilton *et al* 2001, Mulholland *et al* 2001, and Wollheim *et al* 2001), but ^{15}N has also been used to study uptake length based on seston and consumers (Wollheim et al. 2001). Although differentiation did occur in this study, retention patterns were not necessarily generalized for each sample compartment and depended greatly on the stream environment.

Among compartments, seston was expected to show a longer uptake length than either *Carex* or FBOM in all outlets, representing a highly mobile particulate N compartment that partially exchanges with the FBOM compartment as it settles and becomes resuspended. In the three outlets where seston $\delta^{15}N$ was studied, the pre-enrichment regressions either were not significant (NE-12 and GTH 99) or were positive (GTH 153). The non-significant regressions suggest that seston entrainment into the water column was in equilibrium with seston delivery from upstream, resulting in no net retention of ^{15}N from enrichment in previous seasons in this mobile particulate compartment. However, significant negative regression coefficients were calculated for post-enrichment seston $\delta^{15}N$. In each case, the uptake lengths based on these regressions were longer than those derived from post-enrichment FBOM, consistent with the more mobile nature of seston compared to the FBOM compartment as a whole (Newbold *et al* 1983). Furthermore, the difference between pre-enrichment versus post-enrichment seston also suggests that the easily entrained particulate N component was removed from NE-12 and GTH 99 outlets over winter and spring, and was only retained during the summer season. In contrast, the significant positive regression observed for pre-enrichment seston $\delta^{15}N$ in GTH 153 does suggest non-equilibrium dynamics of lake-derived seston, although the peak $\delta^{15}N$ value for seston was observed between 368m and 408m from the lake (Fig. 3C).

FBOM retention patterns were more variable among outlets than seston patterns. In NE-12 outlet, although there was a significant regression coefficient, the 200 m uptake length estimate for pre-enrichment FBOM suggests that little lake-derived N was retained

in this compartment over winter, as the outlet was only 130 m long. In the GTH 153 outlet, pre- and post-season FBOM $\delta^{15}N$ appeared to be very similar (Fig. 3), although only the post enrichment pattern showed a significant regression. The non-significant pre-enrichment pattern may be misleading. Rather than showing no longitudinal pattern, $\delta^{15}N$ of FBOM fluctuated considerably along the transect and showed low and high values in many of the same sampling locations as it did in the post-enrichment samples. Previous studies of N retention in areas with complex channel morphology and riparian development have shown that streams exhibit hotspots of N retention and denitrification, where a hot spot is a region of relatively high uptake or denitrification relative to the surrounding area (McClain *et al* 2003, Groffman *et al* 2005). In this case, the channel habitat heterogeneity in GTH 153 with interspersed pools, runs, and riparian wetlands may have influenced N processing differentially along the reach.

In contrast with FBOM and seston, *Carex* retained similar amounts of N in early season and late season samples from all outlets. Lack of a significant difference in pre- and post-enrichment *Carex* suggests that *Carex* utilizes N derived from previous seasons that is retained in pore water, rather than being linked to short-term delivery. In the Arctic, approximately 10% of aboveground green tissue survives over winter, making retention in biomass of previously supplied ^{15}N potentially very important (Bliss & Grulke 1988). Edwards and Jeffries (2010) found evidence suggesting N acquired in early spring is mainly used for *C. aquatilis* root growth and can be stored in the roots for weeks or months. The study also suggested that shoot growth in early spring relies on N uptake stored from the previous year. Overwintered shoots grow rapidly in the spring

reaching maturity in late June to early July. Lake ^{15}N enrichment during the 2008 season took place around the same time overwintered *Carex* shoots reached maturity. Most of the sedge growth had already taken place before exposure to the newly added ^{15}N during the season; therefore ^{15}N used during this growth period would have been supplied from previous seasons. However, *Carex* continues to produce new shoots through late July, although at a slower rate. Lack of a difference between pre- and post-enrichment *Carex* $\delta^{15}N$ values seen in all of the outlets, despite large variability in $\delta^{15}N$ among outlets in other N compartments, suggests that little of the N supporting this new growth was derived from the 2008 enrichment. In contrast, lack of a significant longitudinal pattern in $\delta^{15}N$ of both FBOM and seston in pre-enrichment samples suggests that overwinter retention was relatively low in both of these compartments.

Comparison of ^{15}N retention among outlets

Changes in physical characteristics are linked to changes in discharge, which in turn influences biological characteristics (Vannote *et al* 1980). It is well established that uptake length is a function of stream discharge across broad geographic scales (Peterson et al. 2001). Within the Arctic Foothill region, Wollheim *et al* (2001) showed that S_w increased with discharge across six stream reaches which ranged in discharge from 0.06 - 26.3 m^3/s. The four streams investigated in the current study were all relatively small and exhibited little variability in discharge between streams (0.012 – 0.0295 m3/s). Of the components and time periods studied, only pre-enrichment *Carex* and post-enrichment FBOM and seston presented more than two significant uptake length values such that uptake length versus discharge could be evaluated (Fig. 7). Of these, uptake length was

not significantly related to discharge. Although there seemed to be a trend in pre-enrichment *Carex*, over this narrow discharge range the relationship between uptake length and discharge was weaker than that seen by Wollheim *et al* (2001).

Discharge is a dominant factor controlling N retention in streams over a wide range of stream sizes (Wollheim et al. 2001, Peterson et al. 2001). Stream habitats will differentially retain N depending on water residence time, macrophyte exposure and geomorphology. Water velocity increases with stream gradient, reducing water residence time, and consequently, time for sedimentation of seston to the FBOM compartment (Saunders & Kalff 2000). The higher gradient NE-12 and GTH 99 outlets showed a pronounced difference in longitudinal patterns of pre-enrichment and post-enrichment seston $\delta^{15}N$, and no evidence for significant retention of overwintered N in the readily entrained particulate compartment. In contrast, the lower gradient GTH 153 outlet showed significant regressions for seston $\delta^{15}N$ in both early season and late season. Likely, these contrasting patterns reflect the differences in water residence time. Longer water residence time in the low gradient outlet would have led to more over winter N retention in the mobile particulate N compartment. Conversely, faster water movement in the higher gradient outlets would have resulted in higher net movement of mobile N, such that over winter N retention was low, leading to a greater difference in pre- and post-enrichment $\delta^{15}N$ of seston along the transects.

Stream geomorphology also appears to control exchange between FBOM and seston compartments. In the GTH 99 outlet, which had the steepest gradient of all outlets studied, seston and FBOM compartments showed similar patterns of $\delta^{15}N$ enrichment.

This suggested that these compartments were tightly coupled. GTH 99 outlet also had a confined channel and was shallow throughout, additional conditions that are not conducive to FBOM retention. Thus, the observed pattern of tight coupling between FBOM and seston in GTH 99 outlet may reflect both low water residence time as well as a lack of depositional habitat in this high gradient stream.

GTH 153 outlet had the highest habitat heterogeneity of the four outlets studied, which may explain the high longitudinal variability in N retention. Lack of a significant difference between pre- and post-enrichment *Carex* and FBOM $\delta^{15}N$ values from GTH 153 suggests that retention of these N components was in equilibrium with delivery from upstream, despite ^{15}N enrichment in 2008. N retention in *Carex* was lower in the mid-section of the reach (208 m – 368 m) than in either upstream or downstream segments (Fig. 3A). This area of the outlet is characterized by a long channel run, which was distinctly different from the deep, wide pools and short riffles (beaded stream) characteristic of the remainder of the study stretch. The more confined channel in this section may have reduced lateral flow such that *Carex* N was derived from upslope rather than upstream delivery. A similar pattern was observed by Ashkenas *et al* (2004) in an old growth forest stream, where they observed no decline in $\delta^{15}N$ in riparian plant tissues with distance downstream because plants were not directly using surface or subsurface water. In contrast, the long residence time in pools upstream and downstream of this run can account for the observed higher N retention in *Carex*. Seston $\delta^{15}N$ values from GTH 153 outlet differed in pre- verses post-enrichment samples, suggesting that seston retained as part of the FBOM pool from previous seasons experienced significant

transport downstream in early summer. This transport was unlikely to have occurred during spring ice melt when lake and stream discharge is very high, because the streambed is frozen at that time (Best *et al* 2005). Although the role of frozen sediment is not completely understood in small arctic streams, it is clear that there is a lack of significant sediment transport during snowmelts (McNamera *et al* 2008).

From the covariance matrices that were formed, t statistics indicated that the only significant difference in regression slopes was from pre-enrichment FBOM between Lake GTH 153 outlet and Lake GTH 114 outlet (Table 5A, t = 2.0). This significant difference in regression slopes cannot be explained solely by differences in discharge because these two streams had more similar discharge than any other pair of streams. GTH 153 outlet had a more diverse geomorphology, whereas the low gradient GTH 114 outlet consisted of wetland throughout the 208m transect and along the lateral grid (Table 1). Nutrient removal in wetlands is facilitated by high vegetative productivity, and shallow, low velocity waters that facilitate sedimentation (Jansson *et al* 1994). Benoy & Kalff (1999) found that water contact with aquatic plants increased sedimentation rates by increasing water retention time. Increased water residence time promotes denitrification, thereby permanently removing N from the system (Saunders & Kalff 2001).

There was no significant difference in lateral N distribution in FBOM and pre-enrichment *Carex*. Samples of *Carex* and FBOM had strong decreasing exponential regressions downstream in GTH 114 outlet (Table 2, Table 3), yet no difference up to 2 m laterally along the longitudinal transect, which is also consistent with high N retention. It must be noted that all lateral samples were taken from the south side of the channel,

where greater lateral dispersion of water and ^{15}N was expected compared to the steeper north side of the channel. However, given that N uptake length was generally short and that overwintering retention was generally greater for *Carex* compared to other N components studied, it is likely that *Carex* wetland habitats similar to that of GTH 114 outlet are very important N sinks on this landscape.

CHAPTER V

CONCLUSIONS

Although discharge is known to be the major factor controlling uptake length over large scales, the results presented here suggest that geomorphology is also important for N retention at a smaller scale. Results also suggest that the geomorphic setting determines hotspots of N retention. Further investigation of geomorphic characteristics of hotspots would be useful for enhancing understanding of landscape variation in N processing. Also, high retention and lateral distribution of N in a *Carex* wetland during this study suggests that *Carex* wetlands are important N sinks in the Arctic Foothills region of Alaska.

Results of this study indicated that the four oligotrophic arctic lake outlets did retain significant amounts of N in the biotic compartments of dominant macrophytes (*Carex*), fine benthic organic matter (FBOM) and seston. Similar patterns of pre- and post-enrichment *Carex* $\delta^{15}N$ in all outlets suggested that most N supporting *Carex* growth was derived from N sequestered during previous growing seasons. Exponential downstream decrease of $\delta^{15}N$ was seen in post-enrichment samples of FBOM and seston in all outlets. Pre-enrichment FBOM and seston $\delta^{15}N$ varied more between outlets, but was much lower near the lake N source than post-enrichment in three of the four outlets. In the wetland dominated outlet, pre- and post-season patterns in FBOM $\delta^{15}N$ were

indistinguishable, suggesting that N retention was in equilibrium with N loading from upstream

Differences in pre- versus post-enrichment sampling provided insight into long-term retention in the study outlets. Outlets with differences found between pre-enrichment versus post-enrichment seston and FBOM suggested that easily entrained particulate N was removed from those outlets over winter and was only retained during the summer season. In the GTH 99 outlet where seston and FBOM showed similar patterns of $\delta^{15}N$ enrichment, tight coupling of compartments was suggested. In contrast, *Carex* in all outlets had similar $\delta^{15}N$ values in early season and late season samples, suggesting little N sustaining new growth was supplied by the 2008 enrichment and was instead derived from previous seasons. In GTH 153, a high value of $\delta^{15}N$ in seston in the pre-enrichment compared to post-enrichment suggests that FPOM from the previous seasons that is retained over the winter undergoes appreciable movement downstream in early summer.

The wetland of GTH 114 outlet also retained N in both *Carex* and FBOM at least 2 m laterally from the channel to the same degree as within the channel. Post-enrichment *Carex* did show a higher amount of retention at 1 m south, but followed the same strong decreasing pattern as within the channel and at 2 m south. The shallow water and beds of macrophytes of this lateral wetland provided for a relatively long water residence time, allowing lateral distribution and long-term retention of N. Further studies may be useful in determining how far N is able to travel laterally from arctic streams into riparian areas.

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APPENDIX A: TABLES

Table 1: Summary of study sites. Discharge is based on averages from two sites per outlet.

Lake Outlet	**Location**	**Length (m)**	**Channel Sample Sites**	**Stream Gradient Slope**	**Discharge (m^3/s)**	**Geo-morphology**
GTH 99	149º36' N, 68º 30' W	95	10	2.86º	0.0120	Confined channel
NE-12	149º 37' N, 68º 39' W	130	13	2.59º	0.0295	Confined channel, Beads
GTH 153	149º45' N, 68º50' W	512	14	1.25º	0.0178	Confined and open channel, Wetland, Beads
GTH 114	149º14' N, 68º 41' W	208	14	.1982º	0.0161	Wetland

Table 2. Exponential regression coefficients and uptake lengths (S_W) for *Carex*. ns represents values that are not significant.

Lake	Date	Regression Coefficient	R^2	p	S_W (m)
NE-12	pre	-0.008	0.357	0.040	125
	post	-	-	ns	-
GTH 153	pre	-	-	ns	-
	post	-	-	ns	-
GTH 99	pre	-0.031	0.502	0.049	32
	post	-0.015	0.421	0.082	67
GTH 114	pre	-0.010	0.641	0.001	100
	post	-0.006	0.479	0.009	166

Table 3. Exponential regression coefficients and uptake lengths (S_W) for FBOM. ns represents values that are not significant.

Lake	Date	Regression Coefficient	R^2	p	S_W (m)
NE-12	pre	-0.005	0.401	0.027	200
	post	-0.008	0.711	0.001	125
GTH 153	pre	-	-	ns	-
	post	-0.006	0.773	0.004	166
GTH 99	pre	-	-	ns	-
	post	-0.010	0.499	0.022	100
GTH 114	pre	-0.009	0.837	0.000	111
	post	-0.007	0.636	0.002	142

Table 4. Exponential regression coefficients and uptake lengths (S_W) for seston. ns represents values that are not significant.

Lake	Date	Regression Coefficient	R^2	p	S_W (m)
NE-12	pre	-	-	ns	-
	post	-0.005	0.435	0.053	200
GTH 153	pre	0.003	0.502	0.007	333
	post	-0.002	0.495	0.011	500
GTH 99	pre	-	-	ns	-
	post	-0.008	0.766	0.004	125

Table 5. t statistics calculated from multiple regression coefficient matrices for pre- and post- enrichment FBOM. Significant values are indicated with *.

(A) FBOM PRE-ENRICHMENT

	NE-12	GTH153	GTH99	GTH114
NE-12	-	-0.444	-0.652	0.8
GTH153		-	-0.467	2.0*
GTH99			-	1.286
GTH114				-

(B) FBOM POST-ENRICHMENT

	NE-12	GTH153	GTH99	GTH114
NE-12	-	1.452	1.996	1.5
GTH153		-	0.817	0.5
GTH99			-	-0.6
GTH114				-

Full Model: $E[Y] = \beta_0 + \beta_1 \text{distance} + \beta_2 I_A + \beta_3 I_B + \beta_4 I_C + \beta_5 (\text{dis}*I_A) + \beta_6 (\text{dis}*I_B) + \beta_7 (\text{dis}*I_C)$

APPENDIX B: FIGURES

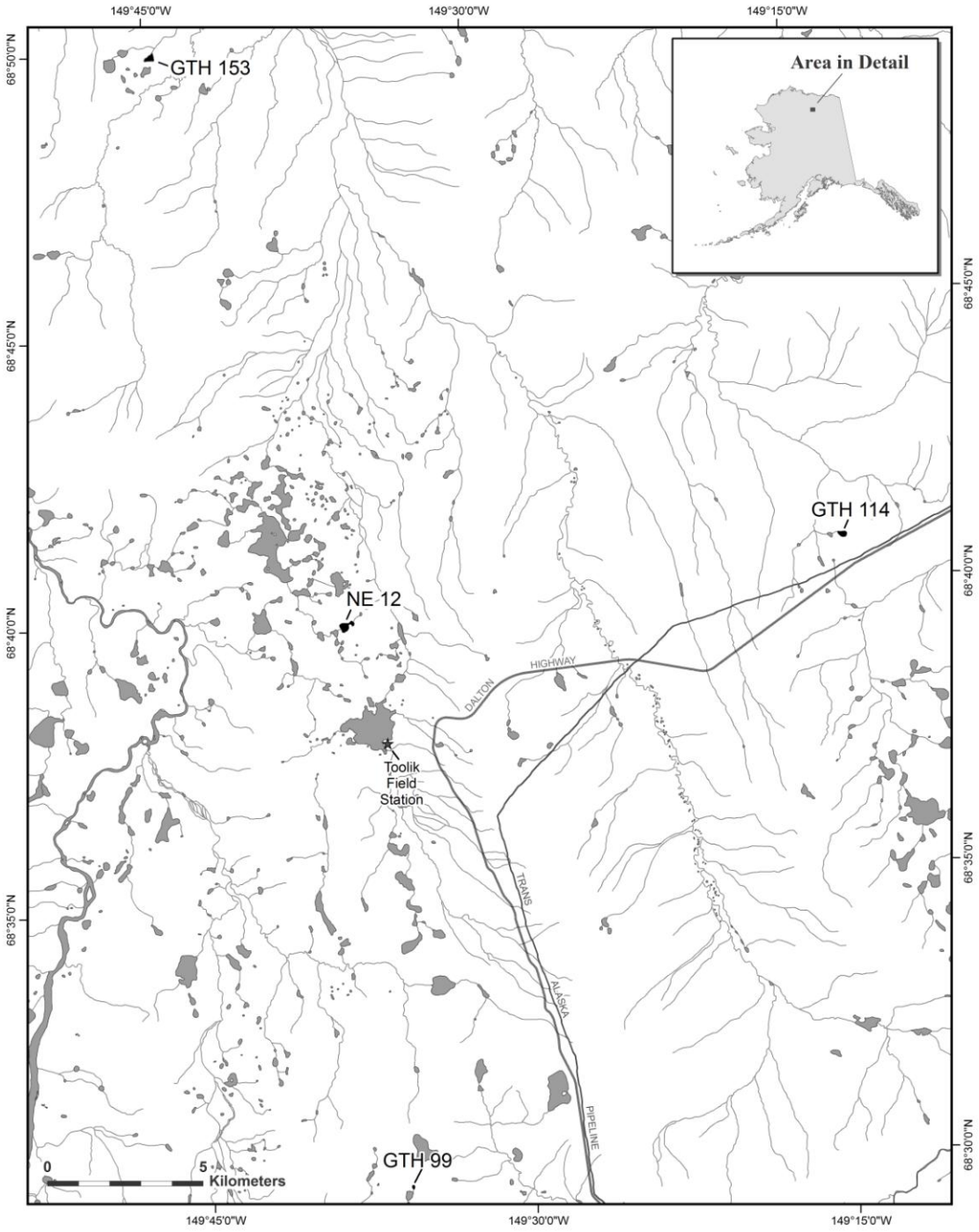

Figure 1. Study area
Study outlets were located on the North Slope of the Brooks Range near Toolik Lake Field Station (68º38'N, 149º38'W) in arctic Alaska.

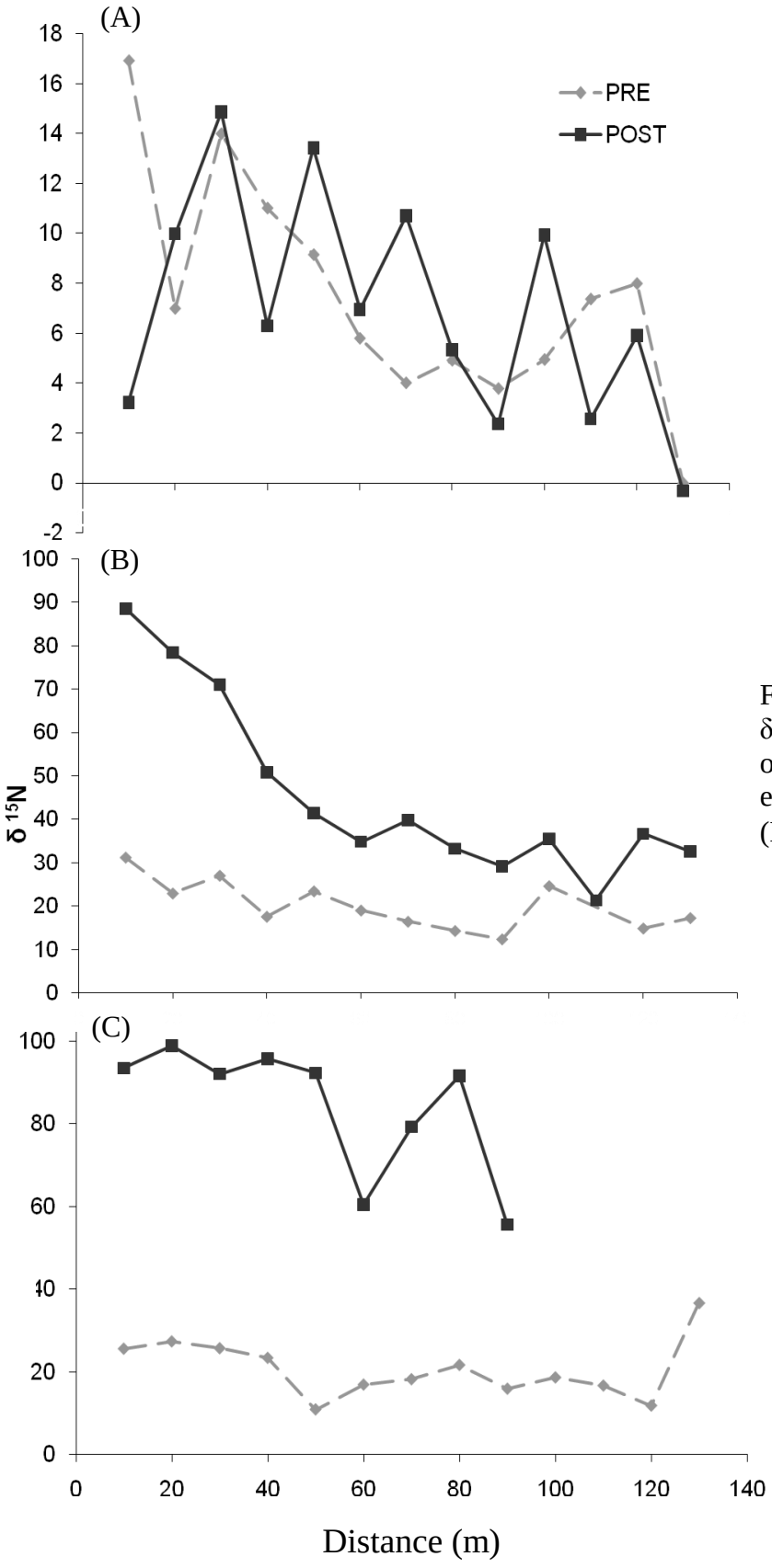

Figure 2. Background corrected $\delta^{15}N$ values from Lake NE-12 outlet for pre and post-enrichment samples of (A) Carex (B) FBOM and (C) seston.

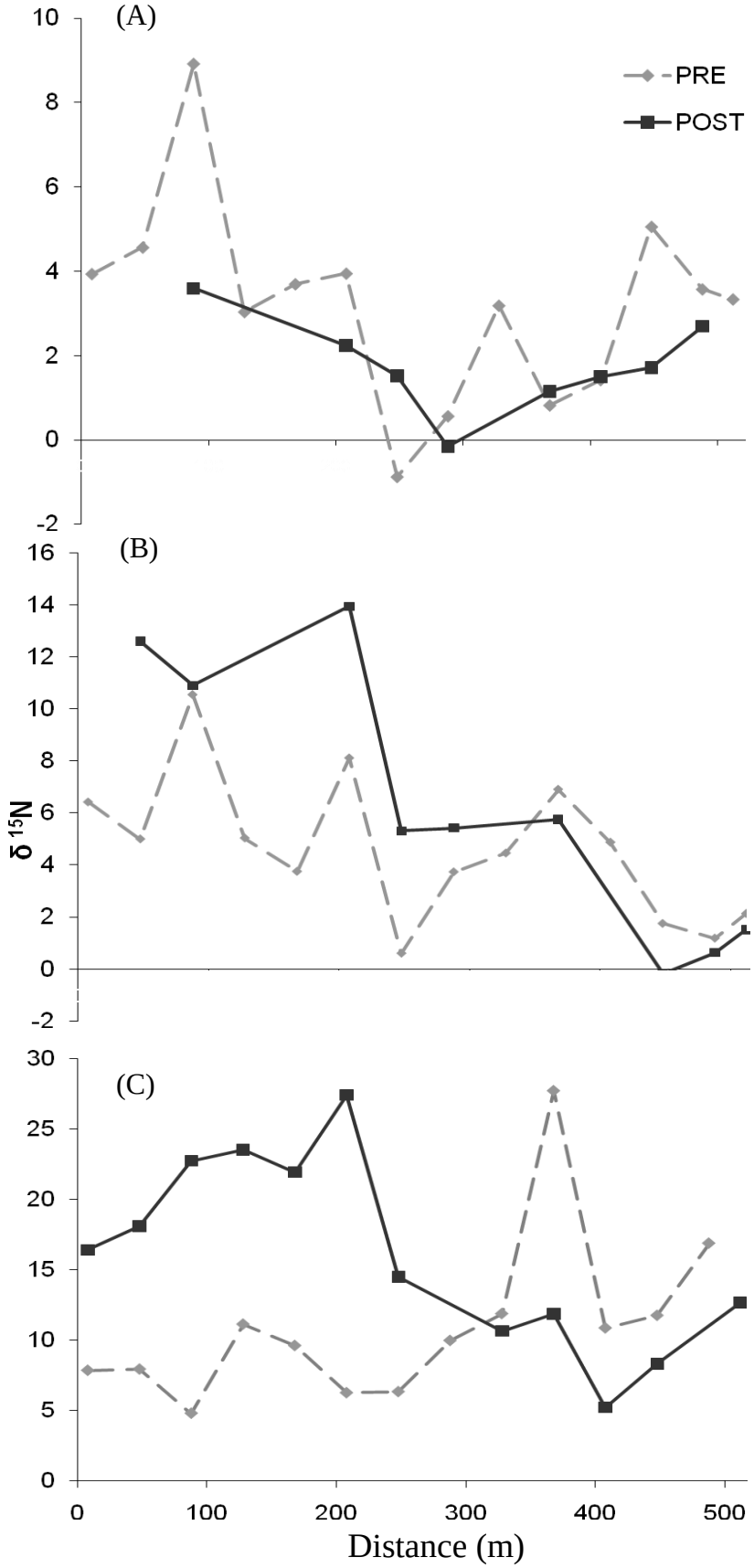

Figure 3. Background corrected $\delta^{15}N$ values from Lake GTH 153 outlet for pre and post-enrichment samples of (A) *Carex* (B) FBOM and (C) seston.

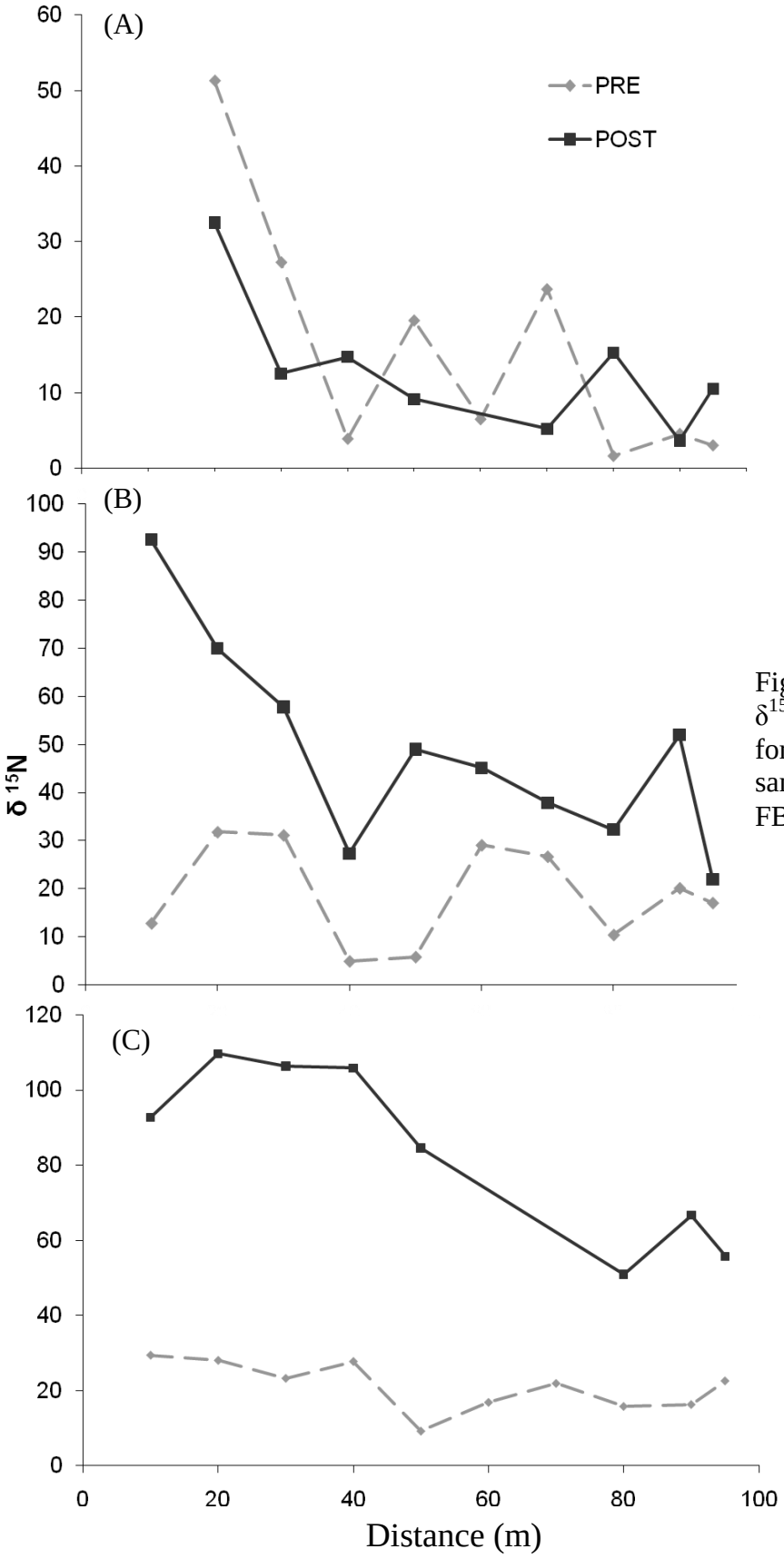

Figure 4. Background corrected $\delta^{15}N$ values from Lake GTH 99 for pre and post-enrichment samples of (A) *Carex* (B) FBOM and (C) seston.

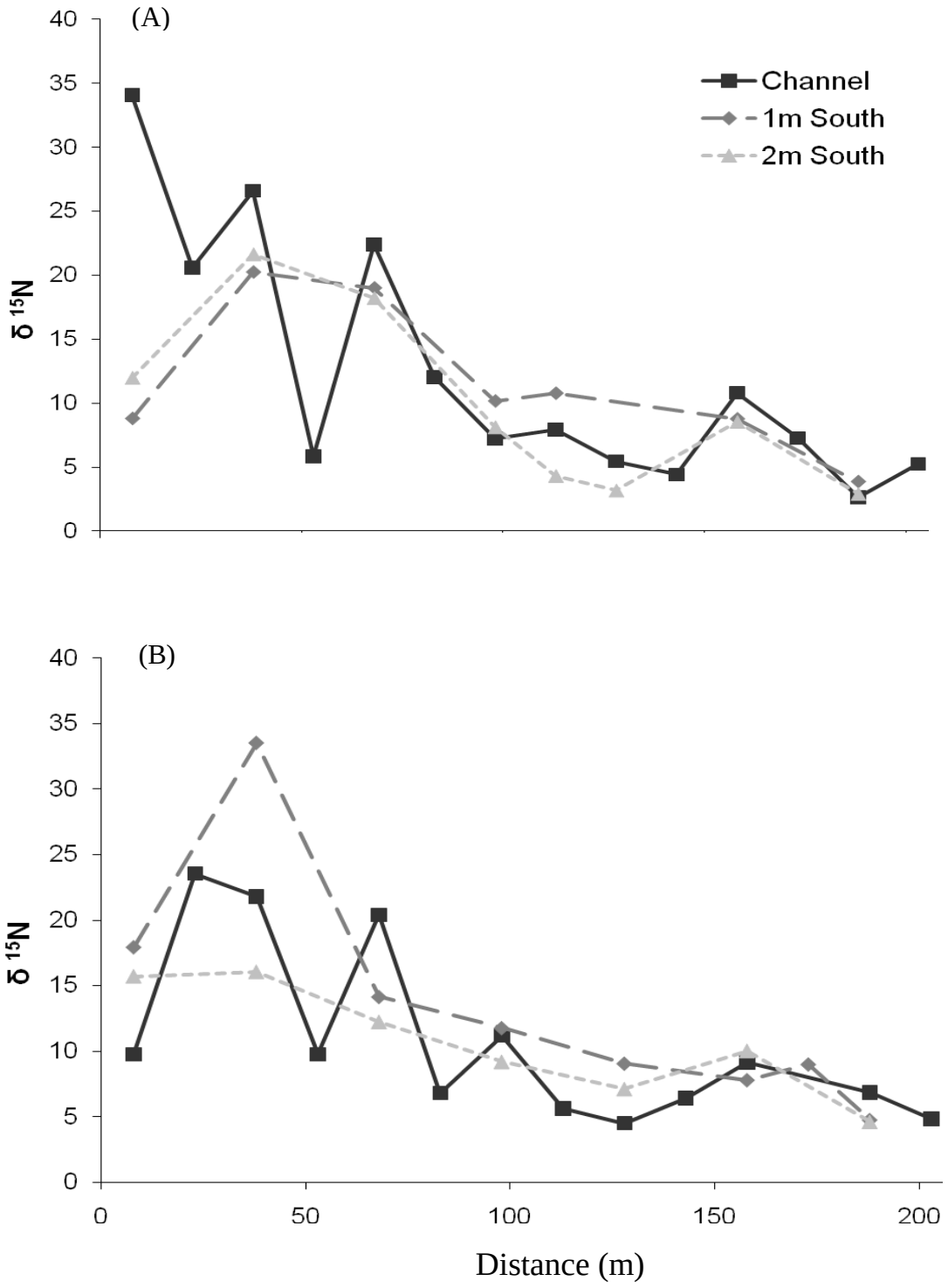

Figure 5. Background corrected $\delta^{15}N$ values from Lake GTH 114 outlet channel and lateral grid (1 m south and 2 m south) for (A) pre-enrichment and (B) post-enrichment samples of *Carex.*

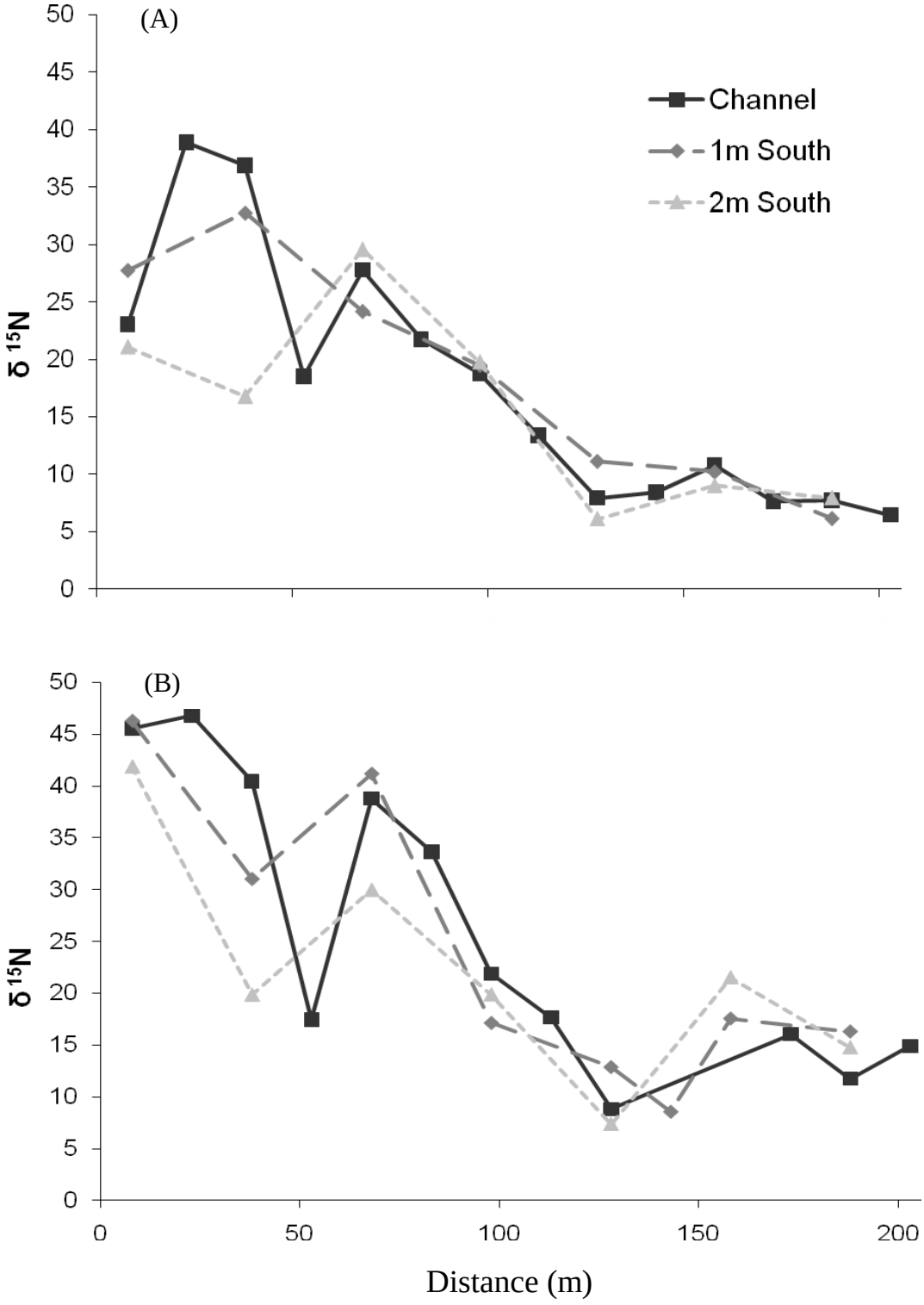

Figure 6. Background corrected $\delta^{15}N$ values from Lake GTH 114 outlet channel and lateral grid (1 m south and 2 m south) for (A) pre-enrichment and (B) post-enrichment samples of FBOM.

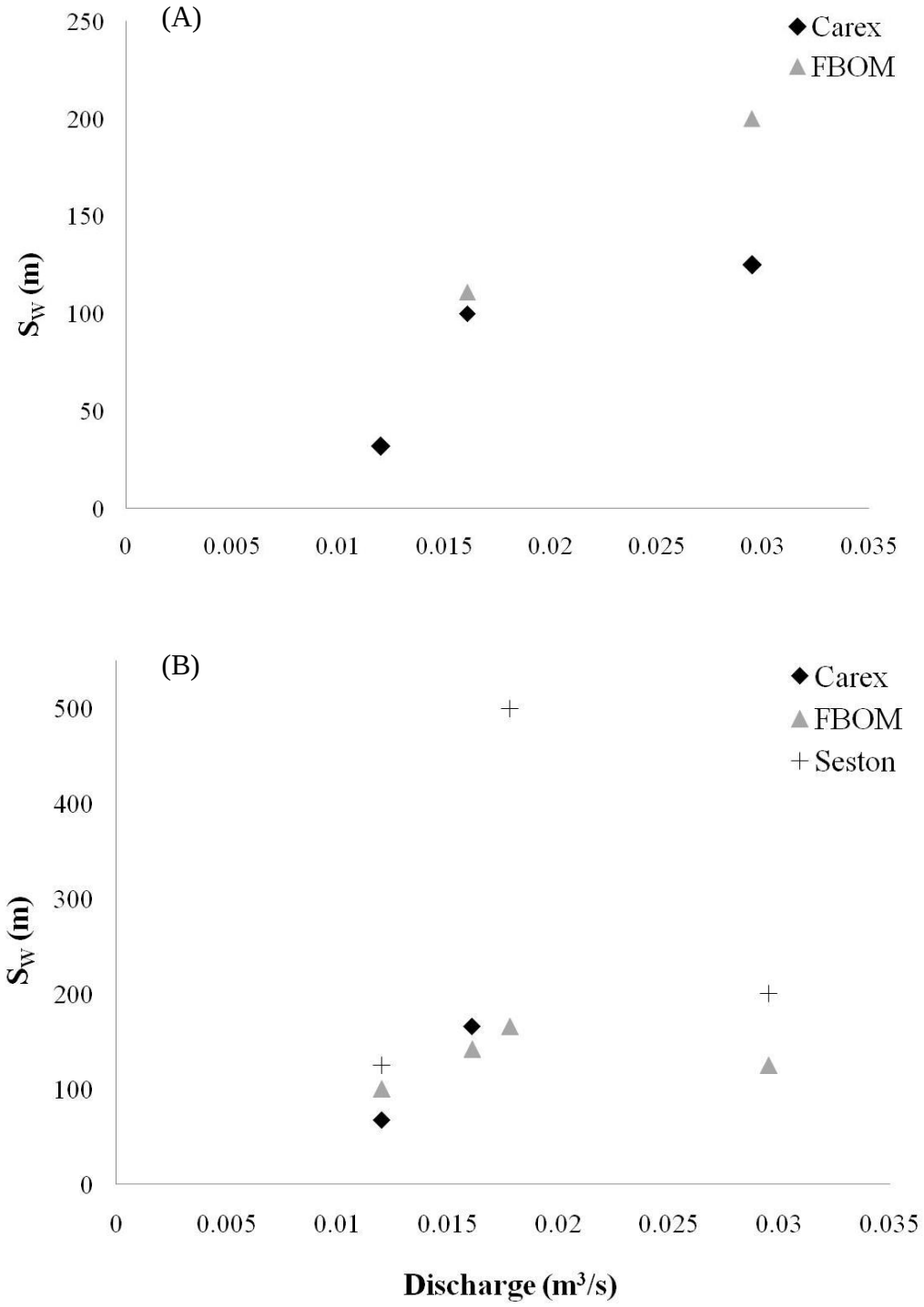

Figure 7. Relation between NH_4 uptake length (S_w) versus discharge measured in (A) pre-enrichment and (B) post-enrichment *Carex*, FBOM and seston for each lake outlet. Only pre-enrichment *Carex* and post-enrichment FBOM and seston presented enough significant uptake lengths to relate to discharge. Outlet discharge was not found to be a significant predictor of uptake length for pre-enrichment *Carex* ($p = .356$, $R^2 = .719$) or post-enrichment FBOM ($p = .794$, $R^2 = .042$) and seston ($p = .999$, $R^2 < .001$).